# Ultra-High-Frequency Notch Filter

## Technical Field

This invention relates to suppression of electromagnetic interference (EMI).

## Background of the Invention

Use of high-bandwidth transmission lines to implement local area networks (LANs) is becoming increasingly common. An example thereof is the Gigabit Ethernet LAN. The high-frequency transmission affected by such transmission lines make suppression of their radiated emissions a significant challenge, on account of the fact that radiated emissions, and the crosstalk to other signal lines caused thereby, increase as transmission frequency increases.

A notch filter is designed to reject a band of frequencies while passing through all other frequencies. Although the use of notch filters to filter out EMI is known (see, e.g., U.S. patent no. 6,539,253), a technical challenge in developing a notch filter for EMI suppression is how to effectively deal with parasitic inductance and capacitance, which can deleteriously affect the intended performance of the filter. At ultra-high transmission frequencies, even small parasitic effects can cause significant problems and therefore must be accounted for in the notch filter design.

## Summary of the Invention

This invention is directed to solving these and other problems and disadvantages of the prior art. According to one aspect of the invention, an apparatus comprises a capacitor having a body and a pair of terminals attached to the body, and a conductor defined on the body and connecting the terminals, the conductor having an inductance defining together with a capacitance of the capacitor a parallel LC circuit. The circuit is tuned by varying the width of the traces. The apparatus is illustratively suited for

use as a notch filter. According to another aspect of the invention, a notch filter having a notch center frequency comprises a capacitor that has a body and a pair of terminals attached to the body and that has a resonant frequency equal to or greater than the notch center frequency, and further comprises a conductive trace that has an inductance and that extends along the body and connects the terminals. Illustratively, when mounted on a printed circuit board (PCB) in a signal line proximate to a ground plane, the notch filter and the ground plane form a virtual conductive loop the product of whose inductance and capacitance is the notch center frequency. According to yet another aspect of the invention, a PCB comprises a signal conductor comprising a pair of discrete conductor segments defined by the PCB, a ground plane defined by the PCB, a capacitor having a body and a pair of terminals on the body that connect the capacitor between the segments, and a conductor defined on the body and connecting the pair of terminals. The conductor has an inductance and forms with the capacitor a notch filter for the signal conductor such that the product of the inductance and the capacitance of a virtual conductive loop formed by the notch filter and the ground plane equals a center frequency of the notch of the notch filter.

Advantages of the invention include a notch filter that is effective at ultra-high frequencies, that is easy to construct, that is tuneable, that minimizes the number of parts used in its construction, that is compact so that it takes up little real estate on a printed circuit board, and that is compatible with surface-mount circuit-assembly techniques.

## Brief Description of the Drawing

These and other features and advantages of the invention will become more apparent from the following description of an illustrative embodiment of the invention considered together with the drawing in which:

Fig. 1 is a perspective diagram of a printed-circuit-board-mounted notch filter that includes an illustrative embodiment of the invention;

Fig. 2 is a graph of load lines of capacitors illustratively used to implement a 1 GHz notch filter;

Fig. 3 is a graph of load lines of capacitors illustratively used to implement a 4.8 GHz notch filter; and

Fig. 4 is a graph of load lines of capacitors illustratively used to implement a 6.25 GHz notch filter.

## Detailed Description

Fig. 1 shows an illustrative embodiment of a notch filter **100** mounted on a printed-circuit board (PCB) **120**. Notch filter **100** spans two segments **124a** and **124b** of a printed-circuit conductor **124** carrying signals that are to be filtered for EMI. Each segment of conductor **124** terminates in a solder pad **126** to which notch filter **100** is electrically connected, e.g., by a component surface-mounting process.

Notch filter **100** consists of a capacitor **102**, preferably a surface-mount capacitor, and a conductive trace **106** of width w and length l defined by (e.g., plated or printed on) and extending the length of body **103** of capacitor **102**. Capacitor **102** is electrically connected to solder pads **126** by conductive terminals **104** that extend from opposite ends of body **103** of capacitor **102**. Trace **106** is electrically connected to terminals **104**, and acts as an inductor there between. Capacitor **102** and trace **106** together form a parallel inductive-capacitive (LC) circuit between the segments of conductor **124**. PCB **120** has a ground plane **122** as one of its layers, which serves as a return path for signals conducted by conductor **124**. Ground plane **122**, capacitor **102**, and trace **106** together form a virtual conductive loop **130** at the resonant frequency of the structure that is formed by them. Loop **130** has a height $h_l$ which is the distance between trace **106** and ground plane **122**. $h_l$ consists of the height $h_c$ of capacitor **102** and depth $h_g$ at which ground plane **122** is buried in PCB **120**. A standard thickness of PCB **120** is 62 mils; consequently, $h_g$ is normally anywhere between 1 mil and 61 mils. The product of the capacitance (C) and inductance (L) of loop **130** define the

center frequency $f_n$ of the notch implemented by filter **100** that will be filtered out of the signals on conductor **124**.

As is known, capacitors have an individual resonant frequency $f_c$ below which they behave capacitively and above which they behave inductively. Typically, the smaller is the capacitance of a capacitor, the smaller is its physical package, and the higher is its resonant frequency $f_c$. For ease of design, it is desirable that $f_c$ of capacitor **102** equal or exceed $f_n$. At this $f_c$, the capacitance C of loop **130** is effectively the capacitance of capacitor **102**. Consequently, the required inductance L of loop **130** is $L = 1/(4\pi^2 f_n^2\, C)$. Inductance L is provided by loop **130**. Inductance L is related to loop height $h_l$ as follows: $L = 5(10^{-3})\, ln\,(\frac{4h_l}{d})\, l$, where L is measured in μH, $h_l$ is measured in mils, $l$ is the length of trace **106** in inches, and d is the diameter in mils of an equivalent circular cross-section having a circumference $\pi d$ equal to twice the sum of the width w and thickness t of trace **106**. L is tuned by varying the width w of trace **106**. It is assumed that the thickness t of trace **106** is a standard and unvarying approximately 1 mil (.~7 to ~1.4 mil) of copper, aluminum, or other conductor; i.e., the standard thickness of a printed circuit trace. Given the dimensions of conventional surface-mountable capacitors, values of L that are reasonably achievable by varying the width w of trace **106** are between about .2 nH and about 1.5 nH.

In this illustrative example, it is assumed that conductor **124** suffers from EMI or crosstalk from a Gigabit Ethernet, i.e., $f_n$=1 GHz. Given $f_n$ and the reasonably-achievable values of L, an available suitable capacitor **102** is selected. In this example, an illustrative commercially-available capacitor is a surface-mountable 0603-type capacitor (length of 60 mils, width and height of 30 mils) of 27 pF. The selection of capacitor **102** determines height $h_l$ of loop **130** ($h_g$ being fixed by PCB **120**) and length $l$ of trace **106**. The inductance L of loop **130** therefore must be tuned to produce the desired value of $f_n$ by varying the width w of trace **106**.

The proper width w of trace **106** is determined from the following formulas.

$$L(h_g, w, t, l) = 5.0\left(10^{-6}\right) \bullet l \bullet \ln\left\{\frac{2\left(h_l + h_g\right)\pi}{(w+t)}\right\} \quad \text{, where}$$

$L$ = inductance (in µH) of loop **130**

$h_g$ = vertical distance from bottom surface of capacitor **102** to the return reference plane **122** (in mils)

$h_l$ = height of capacitor **102** (in mils)

w = width of trace **106** (in mils)

t = thickness (height) of trace **106** (in mils)

$l$ = length of trace **106** (in mils)

$$f_n(h_g, w, t, l, C) = \frac{1}{2\pi\sqrt{L(h_g, y, t, l) \bullet C}}, \text{ where}$$

$f_n$ = center frequency of the notch filter, and

$C$ = capacitance (in farads) of loop **130**

***The procedure for determining w, and $h_g$ for fixed t, l, and C values is as follows:***

*(1) Plot $f_n(h_g,w,t,l,C)$ for $1 \leq h_g \leq h_{pcb}$ (total thickness of PCB **120** in mils) and $\frac{h_l}{5} \leq w \leq h_l$ in mils as a surface plot, with $h_g$ as the x-axis and w as the y-axis. The vertical z-axis is then the resonant frequency for a given $(h_g,w)$ pair.*

*(2) Superimpose a "reference" surface plot on top of the surface plot generated from step (1) that represents the desired resonant frequency $f_n$. This surface plot will necessarily be a planar surface and should cover the entire $(h_g,w)$ range of values as stated in step (1).*

(3) *The intersection of the surface plot from (1) and the planar surface plot from (2) represents the full range of ($h_g$,w) pairs that will produce the desired resonant frequency. This intersecting contour will be a line, referred to as a load line. Implement the solution by fabricating an electroplated copper trace* ***106*** *of length l (mils), and width w (mils).*

(4) *If no intersection results from step (3), alter the value of the capacitance C until an intersecting contour is generated from the two surface plots. Make sure to select C such that this capacitor behaves capacitively slightly beyond the desired resonant frequency. In other words, the selected capacitor must have a resonant frequency $f_c$ that exceeds the desired resonant frequency $f_n$ of the notch filter.*

(5) *If the variable $h_g$ is known a-priori, then select the ($h_g$,w) pair that lies on the load line determined from step (3). Implement the solution by fabricating trace* ***106*** *of length l, and width w. Usually $h_g$ is known a-priori, since the layer stackup of printed circuit board* ***120*** *is known before designing the notch filter.*

Fig. 2 shows a load line **204** that defines the value of w as a function of $h_g$ at $f_n$=1 GHz for a 27 pF 0603-type capacitor. As described above load line **204** is derived by superimposing two surface plots, with their intersection being the load line for a given notch filter center frequency fn.One of the surface plots is a plot of the achievable resonant frequencies as a function of the width w of trace **106** and the depth $h_g$ of the reference return path. This surface plot is for a given fixed capacitance of 27 pF in this example. Also, in this example, $h_l = (30 + h_g)$ mils. Next, a reference plane is superimposed onto the aforementioned first surface plot. This reference plane is the desired notch filter resonant frequency $f_n$ of 1 GHz in this example. The intersection of these two surfaces is line **204** that highlights the needed width of trace **106** as a function of the depth $h_g$ of ground plane **122** within printed circuit board

**120**. The 27 pF 0603-type capacitor is currently believed to be the only capacitor that will provide a 1 GHz notch filter for any depth of ground plane **122** within a conventional 62 mil thick printed circuit board **120**. There are other capacitor values that can provide a 1 GHz notch filter; however, these other values will prevent the depth $h_g$ of ground plane **122** from covering the entire 62 mil thickness of PCB **120**. In these cases, the depth $h_g$ of ground plane **122** must be greater than some minimal depth, or will only work within some subset of the entire 62 mil PCB thickenss. These constraints are restrictive and limit the practicality of using anything but an 0603-type 27 pF capacitor.

Computer simulations indicate that notch filter **100** constructed as described above produces an attenuation better than 7 dB of the 1 GHz EMI.

Instead of using one capacitor **102** and trace **106** to implement notch filter **100**, a plurality of capacitors can be connected in parallel to form capacitor **102**, and one or more of those capacitors can carry traces that together, in parallel, form trace **106**. If capacitors of slightly-different values are used in parallel, the result is a plurality of slightly-different notch filters – or, equivalently, a notch filter having a wider notch – resuting in improved EMI attenuation. One of the advantages of a notch filter **100** constructed in the illustrative manner is that it occupies a very small amount of PCB real estate. To preserve this advantage in the case of a notch filter costructed from a plurality of capacitors, the capacitors may be vertically stacked, illustratively as described in U.S. patent aplication serial no. 10/292,670, filed on November 12, 2002, and assigned to the same assignee as this application. In this illustrative example of a 1 GHz notch filter, a 23 pF 0603-type capacitor may be used in parallel with the 27 pF capacitor. The load line for the parallel combination of the 23 pF and 27 pF capacitors is shown as load line **202** in Fig. 2.

Of course, the invention may be used to implement notch filters at frequencies other than 1 GHz. Illustatively, Fig. 3 shows a load line **304**

for a surface-mountable 0402-type capacitor (length of 40 mils, width and height of 20 mils) of 1.7 pF used to implement a 4.8 GHz notch filter. Correspondingly to the example Fig. 2, the 1.7 pF capacitor may advantageously be used in parallel with a 0402-type capacitor of 1.508 pF to implement the 4.8 GHz notch filter. The load line for the parallel combination of the two capacitors is shown as load line **302** in Fig. 3. Also illustratively, Fig. 4 shows load line **404** for a surface-mountable 0402-type capacitor of 1.023 pF used to implement a 6.1 GHz notch filter. Again, this capacitor may advantageously be used in parallel with an 0402-type capacitor of 0.9 pF to implement the 6.1 GHz notch filter. The load line for the parallel combination of the two capacitors is shown as load line **402** in Fig. 4.

Of course, various changes and modifications to the illustrative embodiment described above will be apparent to those skilled in the art. These changes and modifications can be made without departing from the spirit and the scope of the invention and without diminishing its attendant advantages. It is therefore intended that such changes and modifications be covered by the following claims except insofar as limited by the prior art.